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Simulating spatial changes in vegetation-livestock interactions under different landscape structures: a multi-agent system applied to agro-pastoral territories

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Abstract

Free-range and common-grazing ruminants play a major role in the functioning and the provision of ecosystem services by agro- and silvo-pastoral ecosystems in sub-Saharan Africa. To assess how landscape structure affects the nature of environment-herd-services interactions, this paper describes a Multi-Agent System (MAS) that simulates daily herd movements in a dynamic environment. The model is used to study how the overall productivity of an agricultural territory is affected by the spatial organization of its different landscape units. The originality of this model lies in fine representation, in hourly time steps, of a herd’s movements and activities over the seasons depending on changes in its environment. The herd is likened to a reactive agent with a global representation of its environment. It moves, grazes, drinks, rests and defecates. The model represents the spatio-temporal takeoff of biomass and animal faeces deposits. Grazing occurs between the moving, watering and resting phases, while defecation is continual. Biomass ingestion depends on its relative abundance in the explored plots, while the amount of faeces excreted depends on the amounts of biomass ingested the previous day. This paper describes the first use of the model on a choreme type environment representing a theoretical village territory typical of those found in West Africa. It comprises 5 landscape units: dwellings, compound fields, bush fields, fallows and rangelands. Two scenarios corresponding to 2 different landscape structures were simulated: alley fallows (Sc1), scattered fallows (Sc2). Most faeces deposits were in the fallows (sc1) or rangelands (sc2) in the wet season (4 out of 12 months) and in compound fields in the dry seasons (8 out of 12 months). Alley fallows (sc1) helped to intensify fertility transfers from rangelands to cultivated zones, thereby increasing productivity in cultivated zones (+26%) to the detriment of rangelands (-68%). The presence of ruminants in the territory therefore helped to i) enhance the positive effect of fallows and rangelands in renewing the fertility of cultivated soils and ii) maintain a system of concentric fertility rings with a decreasing fertility gradient from the core (=dwellings) to the periphery of the village (= rangelands). This modelling work thus helps to explain how landscape heterogeneity seen in African village territories is constructed.

Keywords: multi-agent system, agro-pastoral ecosystem, ruminants, organic matter, Sub-Saharan Africa

1. Introduction

Herds in sub-Saharan Africa, especially extensively farmed ruminants, play a major role in the functioning and the provision of ecosystem services by agro- and silvo-pastoral ecosystems. They consume the natural vegetation (grasses, bushes, trees) and some of the biomass produced by cultivated plants; they deposit excreta (faeces and urine), helping to increase soil fertility (Dugué et al., 1998) and plant productivity (Schlecht et al., 2006). Such restitution of organic matter is essential as farmers have limited access to mineral fertilizers (Sanchez, 2002). The extensively farmed animals move around and affect major fertility transfers in spatial terms (Manlay, 2000). Their spatial behaviour largely depends on the choices and practices of agro-pastoralists (Canal et al., 1998), but also on their environment (Chirat, 2010) and how it changes over the seasons and from one year to the next, depending on the climate and the actions of the animals (grazing, biomass restitution), among other things. The dynamics of such multiple environment-herd-services interactions are complex and need to be analysed to improve sustainability in agro- and silvo-pastoral ecosystems.

Modelling is useful when analysing complex systems (Bryant and Snow, 2008). Most modelling work of pastoral systems has focused on the grazing process, i.e. relations between animals and forage resources (Baumont et al., 2002; Mechoud et al., 2000). Some models seek to determine which elements of the rangeland, both biotic (forage resources) and abiotic (land layout) polarize herds depending on livestock farmer practices and herd characteristics (Cambier et al., 2005; Chirat, 2010). Such work precisely describes the spatial and grazing behaviour of herds, but it does not truly represent herd-environment interactions, despite their importance in the functioning of the ecosystems studied. Some rare models describe the functioning of agro-pastoral territories and explain how animals help to maintain soil fertility by showing the redistribution of organic matter in the landscape (Baudron et al., 2014; Belem et al., 2011). However, such a representation remains simplified. Indeed, such models do not show actual herd movements in space, only identifying the main sites where they are present per month or per season, and distinguishing between biomass offtake (common grazing) and restitution (night paddocking). A finer representation of animal movements seems necessary to show how landscape structure affects offtake/restitution and thereby animal-environment interactions (Sané et al., 2015).

This article describes a Multi-Agent System (MAS) simulating daily herd movements in hourly time step, in order to assess how landscape structure affects the spatial organization of biomass offtake/restitution and fertility transfers, and to assess their consequences for productivity in the different landscape units of a given agricultural territory. It is used here to study agro-pastoral village territories occupied by ruminant livestock. This type of spatial and social organization predominates in sub-Saharan Africa (Augusseau, 2013; Manlay et al., 2004). Village territories are territories exploited and managed by human communities. Today, the village territory is recognized as the ideal unit for agricultural development interventions and for its strong community dimension (Basset et al., 2007). Indeed many resources, such as rangelands and crop residues, are still managed collectively. This article describes the MAS and the main concepts involved. The MAS is then used to study two territories with different landscape structures.

2. The Model

2.1. General description and concepts involved

The model simulates the spatial distribution of forage biomass offtake and organic manure restitutions of tropical cattle herds in village agro-pastoral territories and their consequences for plant production in the different landscape units. It comprises two main, interacting dynamic components: i) the decision-making component and ii) the biophysical component. They are described in sections 2.2 and 2.3, respectively.

Our model breaks down into three main entities: herd, agricultural territory, time.

The herd is considered as a reactive agent with a global representation of its environment as, in practice, herds are accompanied by herdsmen regularly visiting the entire agricultural territory. Herd behaviour results from a string of different decisions on different spatio-temporal scales. It is influenced by both time and the environment. The five different activities of the herd are: movement, grazing (biomass consumption, possibly with simultaneous movement), watering, resting and defecation. These activities follow a particular programme throughout the day (cf. section 2.2).

The agricultural territory forms the herd's environment. To portray this environment, a theoretical representation of an agro-pastoral village has been constructed in the form of a "choreme" (Brunet, 1980), which is a simplification of reality and seeks to portray territorial complexity using geometrical shapes. While it might seem simplistic, the choreme was rigorously constructed. It takes into account the different landscape units encountered and their respective importance in West African village territories (Vigan et al., 2013; Audouin et al., 2015). It is simulated by a closed grid of 50 × 50 cells of identical size. Each cell represents a vegetation unit (or plot). It is characterized by its size (1 hectare), type of occupancy (dwelling, compound field, bush field, fallow, rangeland, water point: pond and well), and the amount of forage biomass there (depending on occupancy type).

Time affords a dynamic dimension to herd-environment interactions. For each time step of the simulation (one hour) a set of "clock" variables" is specified (current time, day, month, season and year) along with "status" variables (forage biomass available in each plot, feeding requirements and biomass excreted by each herd, etc.) A distinction is made between three practical seasons: wet season (WS), cold dry season (CDS), hot dry season (HDS). Each simulation begins on day 1 of WS in year 1 and lasts a number of years chosen by the user.

The model input variables are: number of herds in the study territory, size of each herd, annual rainfall, length of each practical season, and landscape structure. Some additional variables are used to specify herd behaviour over the day: departure time to rangeland, watering time and time of return to the night paddock.

The main output variables are: daily herd circuits, forage biomass offtake by the animals, average organic manure restitutions and resulting plant production. These variables are available on different time scales (ranging from a day to a year) and spatial scales (ranging from a plot to a territory and including a landscape unit). The data produced during simulations are therefore numeric (data tables), visual (coloured maps with different colour codes) and symbolic (positioning of herd agents in the choreme and their movements over time).

MAS are acknowledged for their ability to represent complex systems with many interacting processes in a spatialized environment. The model was implemented under the GAMA (Gis & Agent-based Modelling Architecture) platform. Although this paper only describes simulations of theoretical choreme-type environments, the GAMA platform was chosen for its ability to integrate a GIS (Taillandier et al., 2014) with a view to simulating true situations under diverse soil and climate conditions (cf. section 4).

2.2. Decision-making component

The decision-making component models the spatial and grazing behaviour of the herd. Its construction is based on the conceptual model designed by Chirat (2010) based on detailed monitoring of herds in a village territory in Senegal.

It describes the activities of a herd as per the following programme: departure of the herd at dawn, an expected period at the pond in the middle of the day and return to the night paddock at sundown. The herd's main activity is foraging. It is able to perceive and understand its environment, enabling it to choose whether to consume biomass in its own cell or in a neighbouring cell with more biomass. On leaving its paddock the herd moves to one of the plant covers depending on the accessible landscape units and on biomass availability in the different cells. It grazes up to watering time. At watering time the herd moves to the nearest watering place. It then rests until it is time to leave the watering place. On leaving there, the herd resumes grazing until it is time to return to the night paddock. Defecation is continual, i.e. for each simulation time step (one hour) the herd excretes faeces and urine whatever it is doing.

Herd behaviour differs according to the season. In WS, the herd has no access to compound fields and bush fields, as they are farmed. In the day, it may roam the rangelands and fallows if the latter are accessible, with watering in ponds around the village. At night, it is paddocked as a priority on the fallows (if accessible), otherwise on the rangelands. In the two dry seasons, i.e. the "common grazing" seasons, the herd mostly grazes in compound fields in CDS and in bush fields in HDS. Night paddocking is in compound fields and watering takes place at wells near dwellings. Indeed, the ponds have dried up. For the moment, the paddocking cell is determined randomly among accessible fields, but it may eventually integrate rules enabling better representation of agro-pastoralist practices (e.g. rules related to the previous plant cover and crop rotation).

2.3. Biophysical component

The biophysical component is based on a simplified modelling of forage biomass production and its consumption by the herd. Plant growth depends on rainfall and the faeces provided by the animals. Conversely, forage biomass availability in the cells determines forage ingestion and, indirectly, faeces production by the herd. The main biophysical functions of the model are defined from data observed for the Senegalese groundnut basin (Grange et al., 2015).

Forage biomass production is the integral of the plant growth rate over time. Plant growth rate (GS in kgDM/ha/h) is assumed to be uniform throughout WS; it does not take into account rainfall distribution during WS. It depends on annual rainfall (R(y) in mm/year) and the faeces provided the previous year (InOM(y-1) in kgDM/ha), as follows:

$$\mathbf{GS = (1/D) \times Ptheo \times Ep \times Ef} \qquad (1)$$

Where D is the duration of WS in hours, Ptheo is theoretical forage biomass production (5000 kgDM/ha/season), and Ep and Ef are dimensionless variables calculated as follows:

$$\mathbf{Ep = 0.001 \times R(y)} \qquad (2)$$

$$\mathbf{Ef = 0.0018 \times InOM(y\text{-}1) + 0.1} \qquad (3)$$

Biomass ingestion and faeces production are two biophysical processes that are linked.

Biomass ingestion (BI_herd_h in kgDM/h) is the most limiting value between the herd's ingestion capacity (IC_herd in kDM/h) and the amount of biomass available in the cell where the herd is at time t (AB_cell in kgDM), as follows:

$$\mathbf{BI\_herd\_h = min\ [IC\_herd\ ;\ AB\_cell]} \qquad (4)$$

The herd's ingestion capacity depends on its size (Nb) in Tropical Livestock Units (TLU) and the maximum ingestion speed of an animal (IC_animal in kgDM/TLU/h), as follows:

$$\mathbf{IC\_herd = Nb \times IC\_animal} \qquad (5)$$

Faeces production on day d (EOM_herd_h (d) in kgDM/h) depends on the quantity ingested the previous day (BI_herd (d-1) in kgDM/day). The herd excretes a proportion Pi (dimensionless) of what it ingested the previous day:

$$\mathbf{EOM\_herd\_h\ (d) = Pi \times BI\_herd\ (d\text{-}1)\ /\ 24} \qquad (6)$$

3. Simulations and results:

3.1. Simulated scenarios

The simulations described below were defined from the characteristics of territories seen in the Senegalese groundnut basin (Audouin et al., 2015). Average rainfall there is around 600 mm/year. The simulated stocking rate is 0.5 TLU/ha, approaching the average stocking rate seen in the groundnut basin. A village territory of 2500 ha and 5 herds of 250 TLU were simulated.

Two scenarios were simulated, corresponding to 2 village territories differing in landscape structure, all other things being equal (notably the areas of the different landscape units). The first scenario (Sc1) corresponded to a territory with grouped fallows forming alleys between compound fields and rangelands. The fallows were directly accessible from the rangelands in WS. The second scenario (Sc2) corresponded to a territory with no farmer coordination and randomly distributed fallows (cf. figure 1). The animals therefore had no access to the fallows in WS as they were surrounded by crops. Only the results of the first 4 years of simulation are shown here as a balance was obtained at the end of the 3rd and 4th year for scenarios Sc2 and Sc1 respectively.

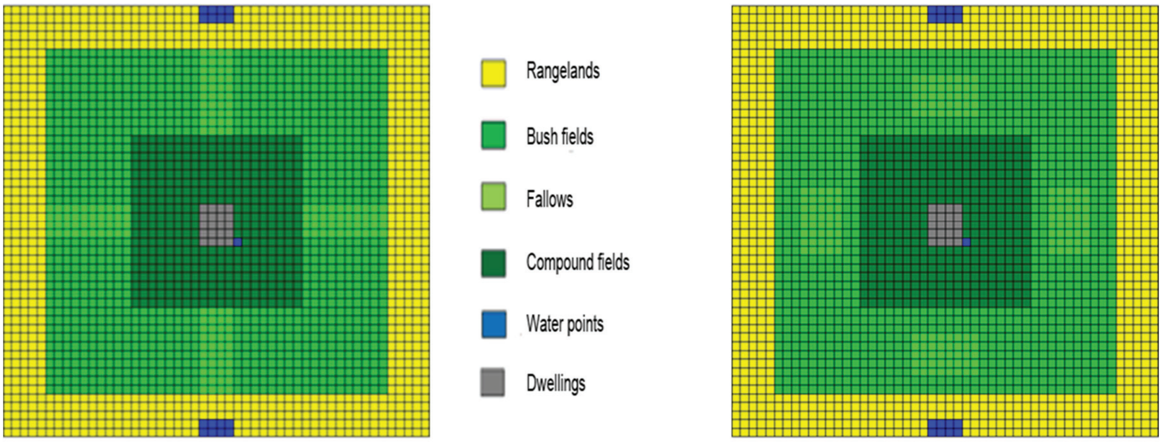

Figure 1. Agro-pastoral territory configurations corresponding to the two simulated landscape structure scenarios: alley fallows (Sc1, on the left) versus scattered fallows (Sc2, on the right)

3.2. Seasonal variation in available forage biomass

Figure 2 shows changes in forage biomass and its distribution between different landscape units over the 4 years of simulation. Whatever the simulation year and scenario, forage biomass increased in all landscape units in WS, reaching a peak at the end of WS (in October). Forage biomass was then no longer produced, only consumed. In CDS, most biomass consumption was in compound fields, while in HDS it was divided between bush fields and fallows. Based on the fourth year of simulation, a comparison of the two scenarios showed that the biomass peak was similar for the two scenarios, i.e. around 1900 kgDM/ha on average throughout the territory. However, the biomass was distributed differently between landscape units. In Sc1 more biomass was produced in bush fields to the detriment of biomass produced in rangelands.

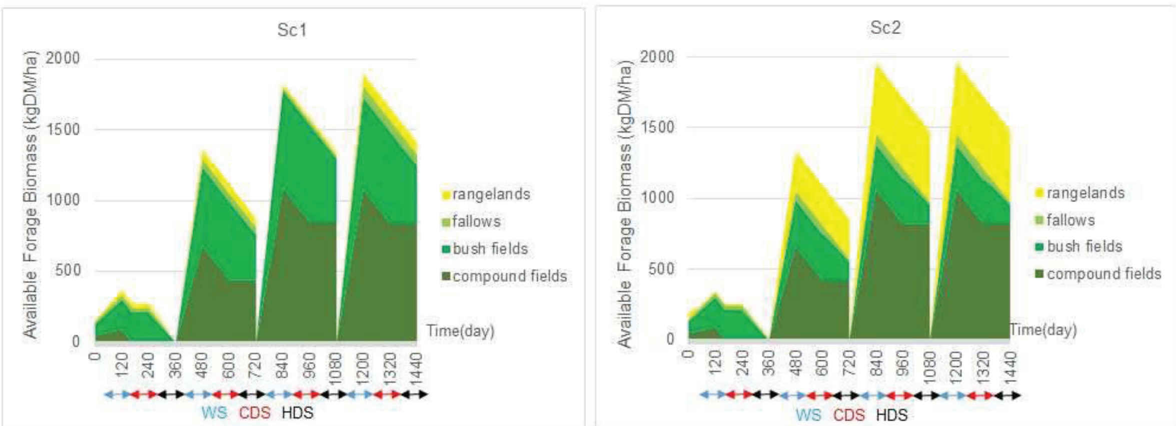

Figure 2. Distribution of available forage biomass between different landscape units depending on whether fallows were organized in alleys (Sc1 on the left) or scattered (Sc2 on the right)

3.3. Seasonal variation in faeces deposits

Figure 3 shows changes in faeces deposits by the herds and their distribution between different landscape units over the 4 years of simulation. Whatever the scenario, daily faeces production was the same in WS and CDS, at around 2kg DM/TLU/day. In HDS, it was slightly less in Sc2 due to lower forage biomass availability in bush fields. Based on the fourth year of simulation, a comparison of the two scenarios showed that the spatial distribution of faeces deposits was not the same in WS as in HDS. In WS, all faeces production in Sc2 was deposited on rangelands, while in Sc1 it was distributed virtually equivalently between rangelands and fallows. Conversely, in HDS more faeces was deposited on fallows in Sc2 as the animals spent more time there. In fact, less forage biomass was available in bush fields and the animals therefore made use of the remaining standing biomass in the fallow in Sc2 (figure 3).

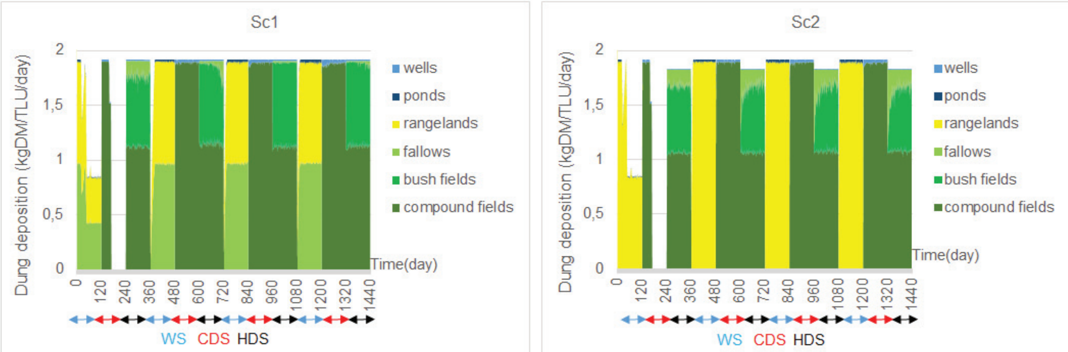

Figure 3. Distribution of the faeces deposits of 5 herds on different landscape units depending on whether fallows were organized in alleys (Sc1 on the left) or scattered (Sc2 on the right)

3.4. Impact of landscape structure on forage biomass production on a landscape scale

Table 1 gives the forage biomass productivity of the main landscape units in the territory at the end of WS in the fourth year of simulation. It shows how landscape structure affects forage biomass production on a landscape scale (Sc1 versus Sc2). Alley fallows (Sc1) increased yield in bush fields by 111%. Compound fields were not affected by the spatial organization of fallow. Thus, the cultivated zones saw an average 26% gain in yields, while rangeland productivity fell 68% with alley fallows.

Table 1. Difference in forage biomass productivity between different landscape units depending on whether the fallow was organized in alleys (Sc1) or scattered (Sc2); data for the end of WS in the fourth year of simulation

	Unit	Scenarios	Compound fields	Bush fields	Total crops	Fallows	Rangelands
Area	ha	Sc1 and Sc2	380	1 040	1 420	160	900
Yield	kgDM/ha/year	Sc1	7 073	1 542	3 022	1 301	442
Yield	kgDM/ha/year	Sc2	6 971	729	2 400	1 296	1 386
Yield differences	%	Sc1 vs Sc2	+1	+111	+26	0	-68

4. Discussion

These simulations show how landscape structure affects the spatial organization of forage biomass production on a landscape scale (Sc1 versus Sc2). Although total forage biomass production was the same from one territory to the next (figure 2) and the spatial heterogeneity of productivity in the different landscape units was high for both scenarios (Sc1 and Sc2), there were some major differences in productivity between the scenarios, especially for bush fields and rangelands. Indeed, when fallows were arranged in alleys (Sc1), there was a 26% increase in yields in the cultivated zones to the detriment of rangelands (-68%) compared to the scenario with scattered fallows (Sc2). When there was no coordination between farmers and the fallows were scattered (Sc2), the herds had no access to the fallows and were paddocked on rangelands in WS. They therefore grazed and deposited all their faeces on rangelands, so there was no fertility transfer during this season. Conversely, alley fallows (Sc1) enabled paddocking on fallows in WS, thereby favouring fertility transfers from natural zones (rangelands) to cultivated zones via the fallows. In fact, the fallow periods were short (1 year), organic fertilization in year n on fallow therefore benefited crops in year n+1. The biophysical component of the model effectively incorporates an after-effect of organic matter restitution (cf. section 2.3 equation 3). These simulations tallied with observations and measurements carried out in real situations which highlighted the importance of fertility transfers effected by herds and their role in constructing spatial heterogeneity (Dugué, 1998; Schlecht et al., 2004; Manlay et al., 2004). This model confirms that agro-pastoralists, through their cropping plan and herd management practices, can concentrate fertility in certain privileged zones where they concentrate their production efforts: fertilizers, labour, etc. (Tittonell et al., 2007).

In the literature, most models simulating village territory functioning in sub-Saharan Africa represent the herds of the village territory as a single herd managed collectively by the village community (Belem et al., 2011; Rufino et al., 2011). Yet, much work shows that herds in West Africa are owned and managed individually on a concession or household scale (Vigan et al., 2013; Audouin et al., 2015). In order to assess simulation sensitivity when modelling herd management (collective or individual), two additional scenarios were simulated, Sc1' and Sc2', keeping the same stocking level (0.5 TLU/ha) and the same landscape structure as in scenarios Sc1 and Sc2 respectively, while grouping all the livestock animals in the territory in a single herd of 1250 TLUs (scenarios Sc1' and Sc2'). The increase in cultivated zone yields was less with a single, collectively managed herd (Sc1' versus Sc2') compared to several herds managed individually (Sc1 versus Sc2). It was +16% for the single herd but +26% with several herds. In the scenarios with a single herd (Sc1' and Sc2'), biomass offtake, hence ingestion and excretion by the animals, were under-evaluated as competition during grazing was over-estimated by an over-concentration of the animals in space. Fertility transfers by livestock calculated by the other models available in the literature are therefore probably under-estimated as shown here with Sc1' and Sc2'.

This paper also presents the results of a model with a simplified biophysical component, primarily comprising empirical linear function type models. Some major work to compare simulation results with field observations remains to be done. Integrating a Geographic Information System (GIS) into the model may increase the realism of the simulations and enable us to compare them to situations found in the field. The model could be assessed on the Saré Yoro Bana case study (South Senegal). For that village territory we have a GIS with parcel plan enabling us to locate and size different landscape units, with a fine description of the spatial and grazing behaviour of the herds present (Chirat, 2010), a yield estimate for all the plots and landscape units in the village territory (Vigan et al., 2013), a detailed inventory of biomass stocks/flows (Vigan et al., 2013), and an estimate of nutrient and carbon flows on a territory scale (Manlay et al., 2004). Other work under way on other territories in other agro-ecological zones of West Africa may also be called upon (Saunier-Zoltobroda et al., 2015; Audouin et al., 2015).

5. Conclusion

To conclude, this article describes an original Multi-Agent System (MAS) simulating how landscape structure affects the spatial organization of vegetation-herd interactions in agro-pastoral village territories. It simulates biomass offtake/restitution (forage, faeces, urine), nutrient transfers and their consequences on different ecosystem services like soil fertility maintenance and crop production in different landscape units of the studied territory. The biophysical component of the model is relatively simple, based on linear empirical models constructed from observations in West African agro-pastoral systems. The originality of the model comes from the fineness of its decision-making component; indeed, herd activities (movements, grazing, watering, resting and excretion) are described and represented in hourly time steps based on rules constructed from detailed herd monitoring.

The first use of this MAS to study agro-pastoral village territories described here clearly confirmed its dynamic representation of how landscape structure affects the spatial and grazing behaviour of ruminant herds. For example, alley fallows inside cultivated fields help maintain fertility transfers from rangelands to cultivated zones, thereby increasing their productivity. The model also showed how extensively managed herds help to establish a system of concentric fertility rings. The latter display a decreasing fertility and productivity gradient from the heart of the inhabited village to the edge of the village. This modelling work therefore helps to explain how landscape heterogeneity seen in African village territories is constructed in favour to diverse provisioning and supporting ecosystem services. The main prospects will be to specify biophysical functions and validate the overall model based on biomass flows and differences in productivity between landscape units seen in agro-pastoral village territories in West Africa. Other ecosystem services controlled by livestock-vegetation interactions such as meat production, pest regulation, carbon sequestration, and water quality may be integrated in a further version of the model.

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